BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Comparison of Chemical and Nuclear Propulsion for Earth Orbital Maneuvering and Translunar Injection Stages - Case 720

DATE: September 5, 1968

FROM: H. S. London

ABSTRACT

Payload-ΔV curves are calculated for nuclear stages at various thrust levels and compared with advanced H_2/O_2 stage performance. Two specific missions are also investigated:

1) transfer from a 100 n.m. altitude, 28.5° inclination orbit to a synchronous equatorial orbit, and

2) injection onto a translunar trajectory following rendezvous of two intermediate-class boosters in a 100 n.m. orbit.

A Nerva I class (75,000 lbs thrust) nuclear rocket stage shows a performance advantage over chemical stages for high ΔV orbital maneuvering applications if there is a requirement for a payload heavy enough so that a Saturn V launch vehicle must be used for the missions. However, the magnitude of this advantage is small unless the ΔV required is considerably in excess of that required for a synchronous equatorial mission, or nuclear system inert weights are much less than those estimated from the NASA-sponsored Lockheed study of a modular nuclear vehicle. If launch vehicles of the INT-20 capability (~135,000 lbs to low orbit) or less are used, nuclear stages have less payload at any ΔV unless the lower inert weights can be attained.

The feasibility of relatively low stage inert weights must be determined on a mission-by-mission basis, taking into account such factors as stage diameter, propellant capacity, thrust level, launch loads, number of restarts, storage time in orbit, and shielding of the crew from radiation.

An engine smaller than Nerva I would give better performance for the classes of missions considered, particularly in conjunction with the lower-capacity launch vehicles. For the synchronous orbit and translunar missions considered, the optimum thrust level is about 25,000 lbs. However, the payload penalty for using either Nerva I (75,000 lbs thrust) or a smaller engine of about 15,000 lbs thrust is not more than 5%.

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MEMORANDUM FOR FILE

Introduction

The use of the Nerva I nuclear rocket for earth orbital maneuvering operations has been under discussion lately as prospects for early manned planetary applications have faded. The context of the discussion has largely been one of ambitious but vaguely defined missions; i.e., large space stations and/or high maneuvering ΔV's, which combined require one or more Saturn V launches. In the light of current NASA prospects, it is well to review the potential application of nuclear rockets to earth orbital missions in terms of smaller launch vehicles and payloads as well as smaller engines compared with Nerva I.

In the mission analysis done in this study, it was assumed that the nuclear stages are operated only after being placed into a low earth orbit, along with the payload, by an all-chemical launch vehicle. Suborbital start of nuclear rockets would significantly enhance their performance payoff (particularly in the Nerva I size or larger); however, this was not considered herein because of the more complicated analysis involved.

Analysis and Results

1. Payload-ΔV Curves

Since specific mission requirements for orbital maneuvering are speculative, general payload-ΔV curves were calculated first. The ΔV's can be interpreted as representing plane change maneuvers, in-plane transfers from one orbit to another, or combinations thereof. Gravity losses are neglected for a first cut analysis since they are expected to be small for plane change maneuvers and, at least with Nerva I size engines, for orbital transfers as well. Aftercooling propellant requirements are also neglected since these only apply to multiple-start cases and are dependent on specific mission profiles.

A vital factor in evaluating nuclear stage performance is the scaling equation used to estimate stage inert weights. The most detailed nuclear stage design study carried out to date was done by Lockheed Missiles and Space Company (see Reference 1). This study was oriented primarily around manned planetary missions, use of the so-called Nerva II engine (which was to have used the 4000-5000 megawatt Phoebus reactor), and uprated two-stage Saturn V launch vehicles so that the nuclear stages were 33 ft. in diameter. Detailed weight estimates were made for a point design, and scaling equations were derived that are applicable to stages having propellant capacity greater than about 150,000 lbs. The Lockheed design concept utilized a shroud which carries the ascent loads during launch and also provides meteoroid protection in earth orbit. This shroud is jettisoned prior to startup of the nuclear stage, but must be accounted for as part of the total weight placed in earth orbit. Based on the Lockheed study, the following equations are used herein as part of Scaling Law 1 (all scaling laws employed in this report are summarized in Table I):

Stage inert weight (excluding the engine) = 17,000 lbs + .08 Wp

Shroud jettison weight = 12,600 lbs + .0775 Wp

where Wp is propellant weight.

A scaling equation for a in-orbit stage to be used for unmanned missions has also been generated by Aerojet through inhouse studies of less depth; their stage inert weight minus engine is given by 13,400 lbs + .064 Wp for the Nerva I system. This was incorporated as part of Scaling Law 2 which assumes the same ascent shroud weight as Scaling Law 1, but a somewhat lighter engine weight for Nerva I (see Table I).

Payload vs. ΔV is plotted in Figure 1 for a gross weight in orbit of 275,000 lbs (i.e., a Saturn V launch vehicle). Nuclear stages using Nerva I are compared with advanced H_2/O_2 stages which are well within the state of the art, and bands of performance are indicated for both nuclear and chemical. The nuclear stage can maneuver greater payload than a single chemical stage for ΔV greater than about 7,000 fps; this payload advantage is about 20,000 lbs for ΔV's of 15,000 fps or more. Percentage-wise this is very large at the higher ΔV's; e.g., for a 60° plane change requiring 25,000 fps, the nuclear payload is approximately double that of a single chemical stage. For missions requiring extreme ΔV's in the range of 35,000-45,000 fps and payloads of 10,000 lbs or less, two chemical stages are competitive with a single nuclear stage.

Similar comparisons are made in Fig. 2 for gross weight in orbit of 135,000 lbs, approximately the capability of INT-20 (SIC/SIVB). The same stage scaling laws were used as in Fig. 1. The results indicate that chemical stages are better than nuclear, at all ΔV's and payloads; the chemical advantage would be even more pronounced for smaller launch vehicles.

A Nerva I nuclear stage would have no capability at all, according to these scaling laws, on a 40,000 lb paylcad launch vehicle, whereas a chemical stage could transfer, e.g., about 13,000 lbs into a synchronous equatorial orbit as indicated by the payload-ΔV curve of Figure 3.

Another way of looking at the preceding results is to crossplot the gross weight required in orbit (i.e., defining the launch vehicle requirements) vs. ΔV for a given payload. This is done for a payload of 40,000 lbs, typical of a MOL-class spacecraft, in Figure 4 and indicates that Nerva I propulsion would result in lower launch requirements only for ΔV's of at least 16,000 fps or more, which is greater than the synchronous equatorial mission requirement.

The reason that the Nerva I nuclear stage performance appears to be so poor, except in the case of a Saturn V launch, is the large fixed weights in the scaling equations. These include the constant term in the stage inert weight equation (13,400-17,000 lbs.), the constant term in the shroud jettison weight equation (12,600 lbs), and the Nerva I engine weight (15,000-18,000 lbs). It is unrealistic to apply these equations, however, to stages which would be used with the smaller launch vehicles because the stages have much less propellant capacity and would be of different geometry than those which were analyzed in the Lockheed study. The missions under consideration in many cases require propellant loadings of well under 100,000 lbs vs. on the order of 200,000 lbs in the Lockheed study; stage diameters would be smaller since they would not be launched on tope of an SII stage, and it is not clear whether the ascent shroud design concept would apply at all.

Two additional scaling laws have been used to determine whether nuclear rockets could be attractive in conjunction with smaller launch vehicles if lower inert weights can be obtained. Scaling Law 3 uses the same Aerojet stage inert weight equation as in 2 (13,400 lbs + .064 W_p) but assumes no additional weight is required for an ascent shroud. Scaling Law 4 is based on a Douglas inhouse study of a SIVB stage, modified to a nuclear rocket configuration (designated SIVB-N) and carrying 60,000 lbs of LH_2 for application to unmanned missions. The stage inert weight in this case is given by 4500 lbs + .1 W_p.

Results based on Scaling Laws 3 and 4 are shown in Figures 5 and 6 for initial weights in orbit of 100,000 lbs and 40,000 lbs., respectively. A small nuclear rocket in the so-called PEEWEE-class, assumed to weigh 4200 lbs (corresponding to about 15,000 lbs thrust), is compared along with Nerva I to chemicals in these two cases. For the 100,000 lb launch vehicle, there is a significant advantage to nuclear vs. chemical only if stage weights as low as those represented by Scaling Law 4 can actually be attained and if a very small (15,000 lbs thrust) PEEWEE-class engine is used rather than Nerva. If the launch vehicle capability is only 40,000 lbs (∿ Titan III M or Saturn IB), chemical stages are better in any event unless even lower inert weights are possible for a nuclear stage. It should be noted, however, that even the Douglas study (Scaling Law 4) was not intended to apply to stages as small as those which would go on Titan III M or Saturn IB (the SIVB-N would be about 75,000 lbs gross weight, including a PEEWEE engine), so the use of nuclear stages on the latter launch vehicles should still not be dismissed without a design study of very small stages, particularly for unmanned missions.

The feasibility of achieving low inert weights on nuclear stages compatible with either Titan III M-class vehicles or the intermediate-class launch vehicles remains to be seen. The effects of stage diameter, launch ascent loads, propellant capacity, thrust level, and crew radiation shielding would have to be assessed for specific missions and launch vehicles.

2. Synchronous Orbit and Translunar Injection Missions

The preceeding discussion has been based on generalized payload-ΔV curves without specifying any particular mission profiles. Aside from orbital plane-change maneuvers, two particular mission applications have been mentioned among others (although these are also speculative): (a) transfer of a manned spacecraft from a low altitude orbit to a synchronous equatorial orbit, (b) injection of an Apollo or post-Apollo spacecraft into a translunar trajectory. A specific suggestion which has been made in the latter case is that manned lunar missions could be carried out without a Saturn V by using earth orbital rendezvous of two intermediate-class launch vehicles which carry a manned spacecraft plus a nuclear stage for the translunar injection.

(A) Transfer to Synchronous Equatorial Orbit

The payload that can be transferred to a synchronous equatorial orbit from a 100 n.m. orbit by a nuclear stage was estimated for an initial weight in orbit of 275,000 lbs, assuming restart of the nuclear stage for the combined circularization/28.5° plane change maneuver at the synchronous altitude. The effects of finite thrust during the first burn were included, using the results of Reference 2. As pointed out in Reference 2, lower thrust-to-weight ratio results in higher gravity losses during the first burn, but also results in a smaller ΔV required for the circularization/plane change impulse, due to the higher altitude at completion of the first burn. Gravity losses during the second burn are negligible because of the low gravitational force at synchronous altitude. Aftercooling propellant required during the approximately 5-hour coast period was estimated from curves shown in Reference 3, based in turn on unpublished data by R. Nixon of MSFC.

Thrust levels of 15,000-75,000 lbs were considered, and both the Lockheed and Aerojet scaling equations--the latter not including an ascent shroud--were used. The results are given in the following table including a comparison with chemical stages.

Isp	Thrust	Assumed Engine Weight	Scaling Equation	ΔV_{total}	Payload	Total Engine Operating Time
825 sec	75,000#	15,000#	Lockheed	14,220 fps	104,900#	1150 sec
	50,000	11,000	"	14,330	108,900	1738
	25,000	6,000	"	14,850	111,200	3572
	15,000	4,200	"	15,720	108,000	6208
	75,000	15,000	Aerojet	14,240	121,800	1247
	50,000	11,000	"	14,360	125,700	1886
	25,000	6,000	"	14,940	127,600	3889
	15,000	4,200	"	15,870	123,800	6877
465 sec	High Thrust	-----	λ=.92 single stage	14,100 fps	92,600	----
	High Thrust	----	λ=.92 two stage	14,100 fps	96,200	----

Thus, nuclear rockets would yield 15-20% additional payload vs. an advanced cryogenic chemical stage for this mission if nuclear stage inert weights correspond to the Lockheed scaling laws, or 30-40% if inerts are closer to the Aerojet scaling law. In either case a thrust level of about 25,000 lbs gives near-maximum payload, but the penalty for thrust levels as high as 75,000 lbs or as low as 15,000 lbs is only about 5%. The reason for the slight difference in ΔV's and engine operating times between the two different scaling laws, at the same thrust levels, is that the jettisoning of the ascent shroud weight prior to nuclear stage ignition in the case of the Lockheed scaling law results in slightly higher thrust/weight ratio at ignition.

(B) Translunar Injection

Injection from a 100 n.m. circular orbit into a translunar trajectory, characterized by an impulsive velocity (no gravity loss) requirement of 10,250 fps, was evaluated for an initial weight in orbit of 200,000 lbs. This figure was selected to represent earth orbital rendezvous of two intermediate-class launch vehicles, and the analysis of the injection stage performance was intended to determine whether such vehicles and stages would be adequate to carry out Apollo or Post-Apollo lunar missions.

Since the upper stage of any of the intermediate-class launch vehicles would undoubtedly be much smaller in diameter than the SII stage and since, if an Apollo spacecraft weighing about 100,000 lbs is the payload, the propulsion stage can gross no more than about 100,000 lbs, the Lockheed scaling equations cannot be expected to apply. Nuclear stage performance has therefore been assessed for this mission on the more optimistic basis of Scaling Laws 3 and 4 (based on the Aerojet and Douglas data, respectively). Again, inert weights as low as those predicted by these scaling laws must be considered speculative in the absence of detailed design studies for this specific mission and a particular launch vehicle.

Nuclear rocket thrust levels of 15,000-75,000 lbs were evaluated as in the previous mission. Gravity losses during the translunar injection burn were taken from Reference 2. The results are given in the table below.

Isp	Thrust	Engine Weight	Scaling Law	ΔV_{total}	Payload	Injection Stage Gross Wt	Burn Time
825 sec	75,000#	15,000#	3	10,400 fps	102,600	97,400#	713 sec
			4		109,200	90,800	
	50,000	11,000	3	10,580	105,600	94,400	1101
			4		112,100	87,900	
	25,000	6,000	3	11,350	106,600	93,400	2296
			4		113,000	87,000	
	15,000	4,200	3	12,450	102,700	97,300	4113
			4		108,900	90,100	
465 sec	High	----	λ=.92 single stage	10,300	91,800	108,200	----

The table shows that the nuclear stage (with optimistic inert weights) can deliver a 100,000 lb spacecraft with some performance to spare, and since the required injection stage gross weight is less than 100,000 lbs, two 100,000 lb capability launch vehicles would be adequate for the mission. As in the synchronous orbit mission, 25,000 lbs is about the optimum thrust level although the payload penalty for going as high as 75,000 lbs or as low as 15,000 lbs is only about 3%. Alternately, a slightly greater launch vehicle capability would accommodate the maximum injected payload capability of a nuclear stage--106,000 lbs or 113,000 lbs for the two scaling laws respectively. The chemical stage, on the other hand, cannot meet the Apollo spacecraft weight requirements; the payload is only about 92,000 lbs and the propulsion stage weight about 108,000 lbs. This indicates that the required launch vehicle capability is sized by the injection stage weight in the case of chemical propulsion, whereas for the nuclear case the required payload sizes the launch vehicle. This is shown in a more concise way in the table below, where the required launch vehicle capability (to a 100 n.m. orbit) is indicated as a function of the required payload, and chemical and nuclear are compared on this basis.

Injected Payload	Injection Stage	Scaling Law	Required Injection Stage Weight	Required Launch Vehicle Capability
100,000#	Nuclear	3 or 4	$\leq$ 95,000#	100,000#
	Chemical	λ=.92	117,800	117,800
106,000	Nuclear	3 or 4	$\leq$101,000	106,600
	Chemical	λ=.92	125,600	125,600
113,000	Nuclear	3 or 4	$\leq$108,000	113,000
	Chemical	λ=.92	130,100	130,100

The point to be made with this table is that for any given injected spacecraft weight, the required launch vehicle capability is 15-20% less if a nuclear rather than an advanced cryogenic chemical injection stage is used.

Conclusions

1. For Saturn V-launched earth orbital missions, a larger payload can in general be carried with a nuclear maneuvering stage than with an advanced cryogenic chemical stage. However, the payload advantage is small unless the maneuvering ΔV requirement is in excess of that required for transfer from a low orbit to a synchronous equatorial orbit, or nuclear stage inert weights are much less than those predicted from the Lockheed scaling laws.

2. The payload for a Saturn V-launched synchronous orbit transfer mission, e.g., is about 105,000-110,000 lbs with a nuclear stage, assuming the Lockheed scaling laws, vs. 90,000-95,000 lbs with chemical. Maximum payload is obtained with a nuclear rocket of about 25,000 lbs thrust.

3. For a MOL-size payload of about 40,000 lbs, a chemical stage has more maneuvering capability than a nuclear stage if the launch vehicle capability to low orbit is about 180,000 lbs or less (assuming single-launch missions). If the launch vehicle capability is that of the INT-20 ($\sim$135,000 lbs) or less, a chemical stage is better for any payload/ΔV combination. These statements hold unless lower nuclear system inert weights can be obtained than those predicted by the Lockheed scaling laws.

4. If inert weights corresponding to either the Aerojet or Douglas SIVB-N weight estimates can be attained, a nuclear stage of less than 100,000 lbs gross weight can inject an Apollo spacecraft onto a translunar trajectory. This means that a manned lunar mission could be carried out with earth orbital rendezvous using two 100,000 lbs payload launch vehicles--one carrying the nuclear stage and the other the spacecraft. The same can be done with a cryogenic chemical injection stage, but the launch vehicle capability to low orbit would have to be 15-20% greater. The optimum nuclear rocket thrust level for this mission is also about 25,000 lbs, although again the penalty for thrust levels as high as 75,000 or as low as 15,000 lbs is very small.

5. Nuclear rockets can be attractive on single-launch missions with launch vehicles of 100,000 lbs capability or less only if low inert weights can be attained <u>and</u> small, PEEWEE size engines rather than Nerva I are used.

Summation

The case for using nuclear rockets in earth orbital missions is tenuous even if high ΔV maneuvering requirements become a reality. In order that performance significantly surpass that of advanced chemical stages for such applications, one or more of the following must apply:

a) Mission requirements for payload sufficiently heavy so that at least one Saturn V-class launch vehicle is needed per mission. This is because scaling effects are such that nuclear stages are most attractive from the performance standpoint in large sizes. However, the very scale of such missions implies costs that would place them well into the indefinite future.

b) Attainment of nuclear stage inert weights considerably lower than those predicted using the Lockheed scaling equations. The Lockheed weights might be considered conservative when applied to earth orbital missions, since they were based on design for long duration manned planetary missions and the use of the 200,000-250,000 lb thrust Nerva II engine, whereas earth orbital missions might require only a few hours lifetime for the nuclear stage and the preferred thrust levels would be much lower. The Aerojet and Douglas weight estimates, on the other hand, may be optimistic particularly as applied to manned missions since they did not consider launch ascent loads or crew radiation shielding. Even the Lockheed weights may be optimistic in regard to the latter since they do not reflect the results of Reference 4, which indicate a much more severe radiation hazard than had been anticipated.

c) Suborbital start of the nuclear rocket (not included in this report). This could have a major impact on nuclear/chemical comparisons not only for earth orbital missions but for lunar and planetary as well. Reference 1 and other studies have indicated dramatic performance yields from suborbital start, because it allots more of the total mission ΔV to the high Isp nuclear system. The major barriers to suborbital nuclear start appear to be political and emotional ones, rather than technical. The Lockheed nuclear stage study (Reference 1), e.g., confirmed the technical feasibility of a system which could effect safe disposal of a nuclear stage for both normal and abort-mode operations.

1013-HSL-nma

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Attachments

TABLE I

SCALING LAWS

#1 $W_{stage\ inert} = 17{,}000 + 0.08\ W_p$

$W_{engine} = 18{,}000$

$W_{jettison} = 12{,}600 + 0.0775\ W_p$

#2 $W_{stage\ inert} = 13{,}400 + 0.064\ W_p$

$W_{engine} = 15{,}000$

$W_{jettison} = 12{,}600 + 0.0775\ W_p$

#3 $W_{stage\ inert} = 13{,}400 + 0.064\ W_p$

$W_{engine} = 15{,}000$ (NERVA I)
4,200 (PEEWEE)

$W_{jettison} = 0$

#4 $W_{stage\ inert} = 4{,}500 + 0.10\ W_p$

$W_{engine} = 4{,}200$

$W_{jettison} = 0$

APPENDIX

The stage mass fractions, $\lambda \left(\equiv \frac{W_p}{W_p + W_{inert}} \right)$, corresponding to the several scaling equations used in this study are plotted vs. propellant loading in Figures 7 and 8 so that the reader can better judge whether these equations are optimistic or pessimistic. Figure 7 does not include engine weight in the total stage inert weights; Figure 8 includes engine weights as indicated. Jettisonable ascent shroud weights are not included in either case.

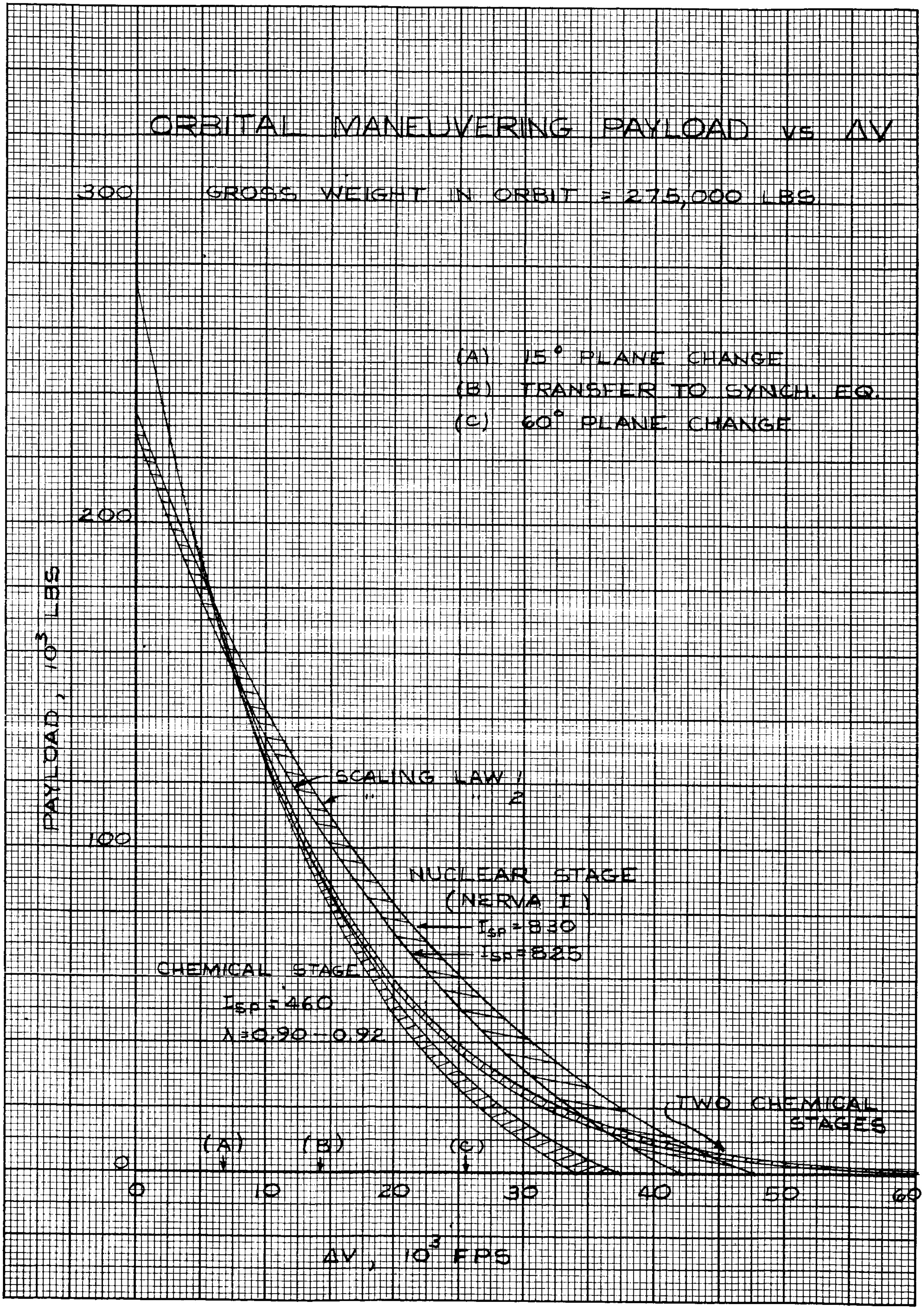
REFERENCES

1. Modular Nuclear Vehicle Study, Phase II-Volume I, Summary, LMSC Report-A830244, February 29, 1968.

2. Finite-Thrust Transfer to Synchronous Orbit and Translunar Injection, Bellcomm Memorandum for File by A. L. Schreiber,

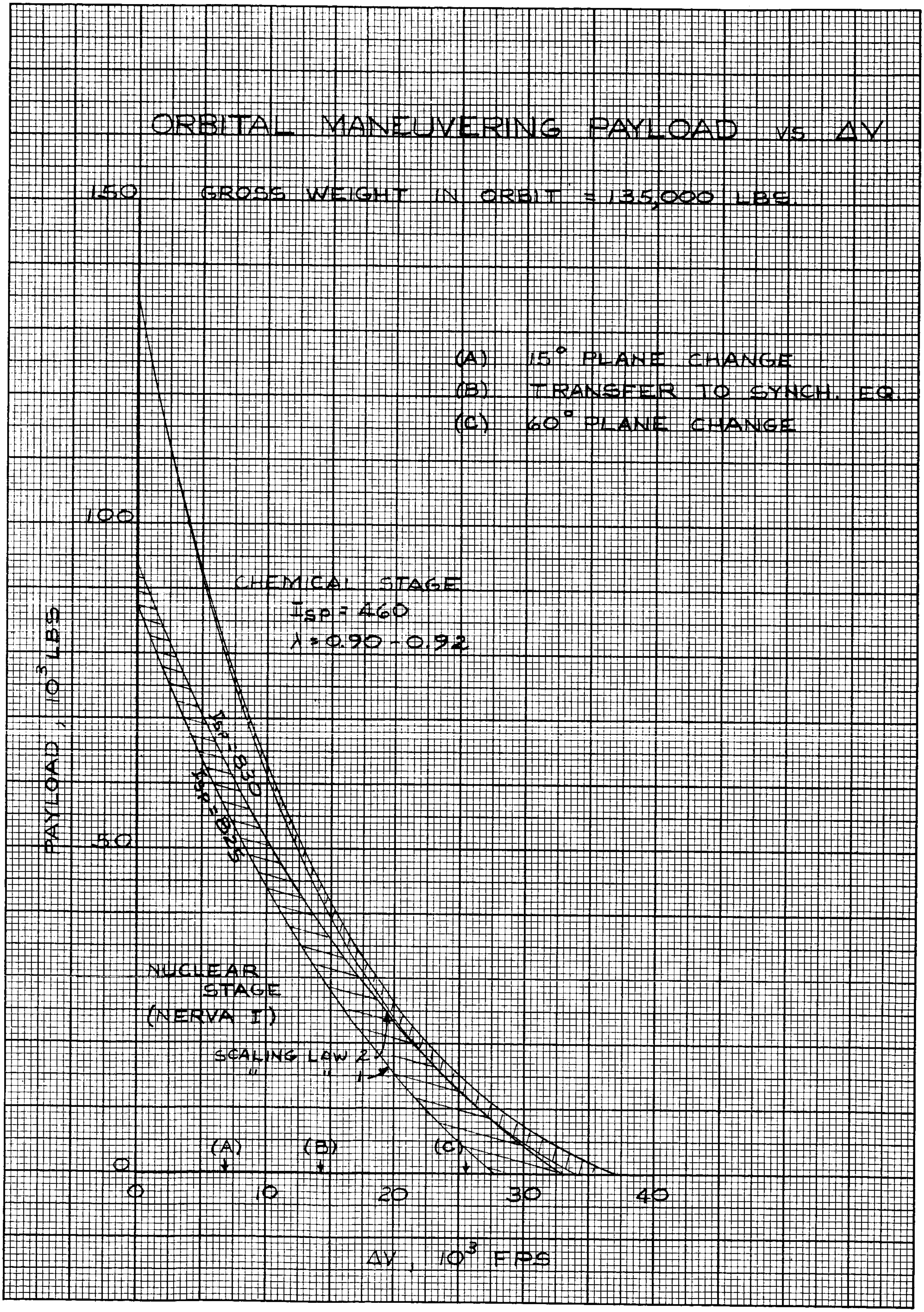
3. Application of Nuclear Rockets to Orbital Operations, by P. G. Johnson - AEC/NASA Space Nuclear Propulsion Office - November, 1966.

4. Modular Nuclear Vehicle Study, Phase II-Volume XI, Nuclear Radiation Environment - LMSC Report-A848446, October 16, 1967.



ORBITAL MANEUVERING PAYLOAD vs ΔV
GROSS WEIGHT IN ORBIT = 275,000 LBS
(A) 15° PLANE CHANGE
(B) TRANSFER TO SYNCH. EQ.
(C) 60° PLANE CHANGE
300
200
100
0
PAYLOAD, 10³ LBS
SCALING LAW 1
" " 2
NUCLEAR STAGE
(NERVA I)
Isp = 830
Isp = 825
CHEMICAL STAGE
Isp = 460
λ = 0.90 - 0.92
TWO CHEMICAL STAGES
(A)
(B)
(C)
0
10
20
30
40
50
60
ΔV, 10³ FPS

FIG. 1



ORBITAL MANEUVERING PAYLOAD VS ΔV
GROSS WEIGHT IN ORBIT = 135,000 LBS.
(A) 15° PLANE CHANGE
(B) TRANSFER TO SYNCH. EQ.
(C) 60° PLANE CHANGE
CHEMICAL STAGE
ISP = 460
λ = 0.90 - 0.92
ISP = 830
ISP = 825
NUCLEAR STAGE
(NERVA I)
SCALING LAW 2
" " 1
150
100
50
0
(A)
(B)
(C)
0
10
20
30
40
PAYLOAD, 10³ LBS
ΔV, 10³ FPS

FIG. 2

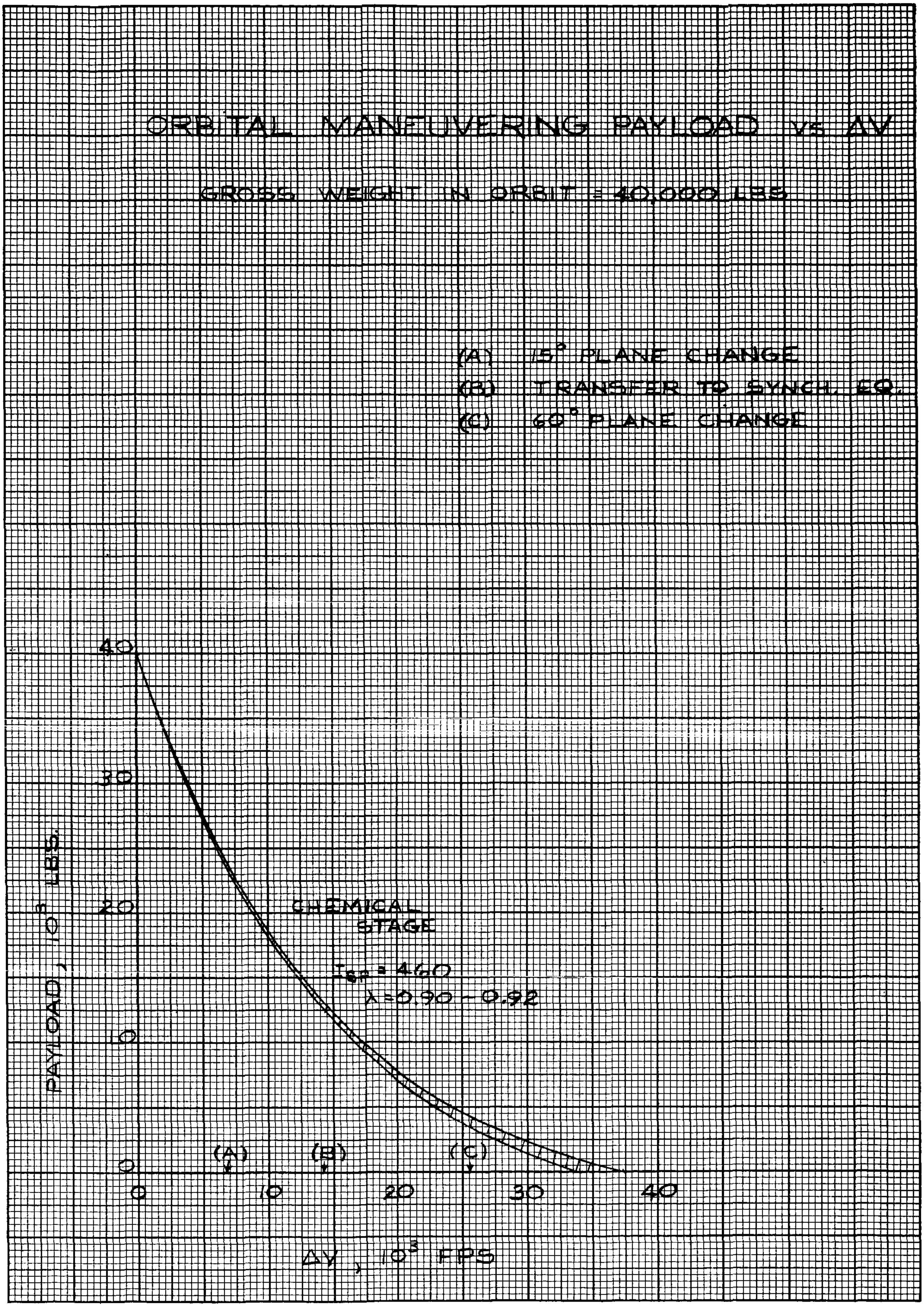

ORBITAL MANEUVERING PAYLOAD vs ΔV
GROSS WEIGHT IN ORBIT = 40,000 LBS
(A) 15° PLANE CHANGE
(B) TRANSFER TO SYNCH. EQ.
(C) 60° PLANE CHANGE
CHEMICAL STAGE
I_{SP} = 460
λ = 0.90 - 0.92
PAYLOAD, 10^3 LBS.
40
30
20
10
0
(A)
(B)
(C)
0
10
20
30
40
ΔV, 10^3 FPS

FIG. 3

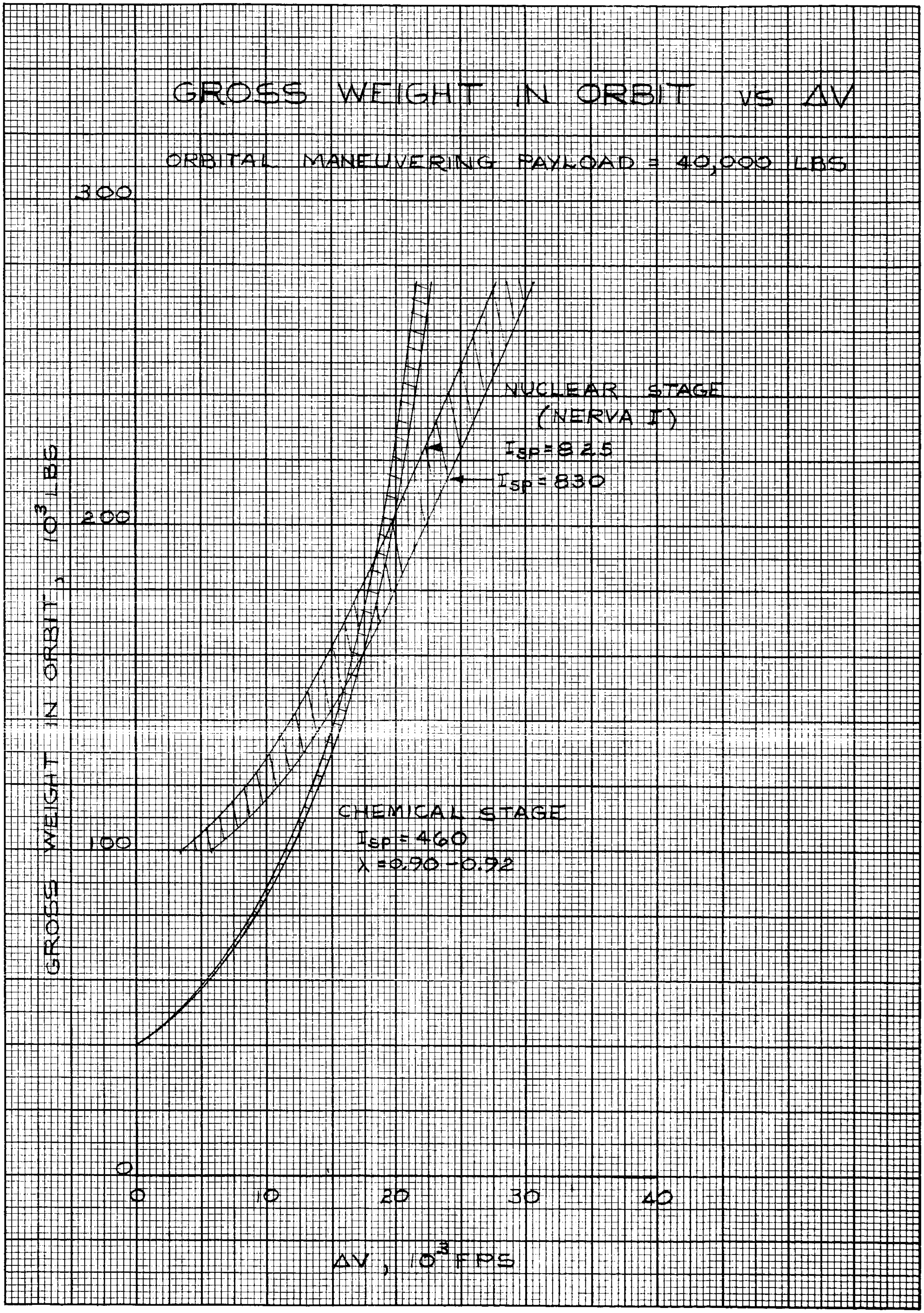

GROSS WEIGHT IN ORBIT vs ΔV
ORBITAL MANEUVERING PAYLOAD = 40,000 LBS
300
200
100
0
NUCLEAR STAGE
(NERVA I)
Isp = 825
Isp = 830
CHEMICAL STAGE
Isp = 460
λ = 0.90 - 0.92
0
10
20
30
40
ΔV, 10³ FPS
GROSS WEIGHT IN ORBIT, 10³ LBS

FIG. 4

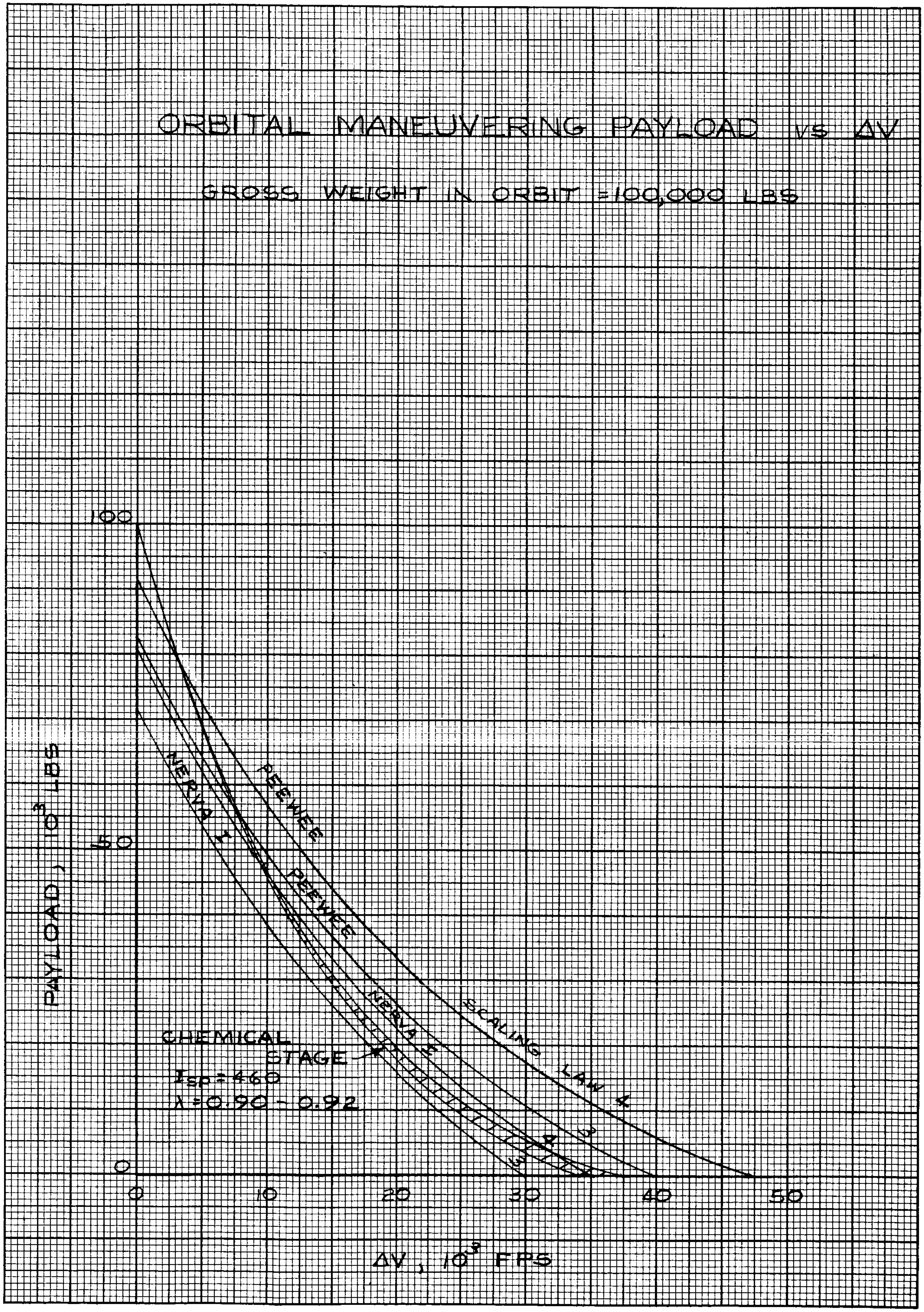

ORBITAL MANEUVERING PAYLOAD vs ΔV
GROSS WEIGHT IN ORBIT =100,000 LBS
100
50
0
PAYLOAD, 10^3 LBS
NERVA I
PEEWEE
PEEWEE
NERVA II
SCALING LAW
CHEMICAL STAGE
I_{sp} = 460
λ = 0.90 - 0.92
4
3
4
3
0
10
20
30
40
50
ΔV, 10^3 FPS

FIG. 5

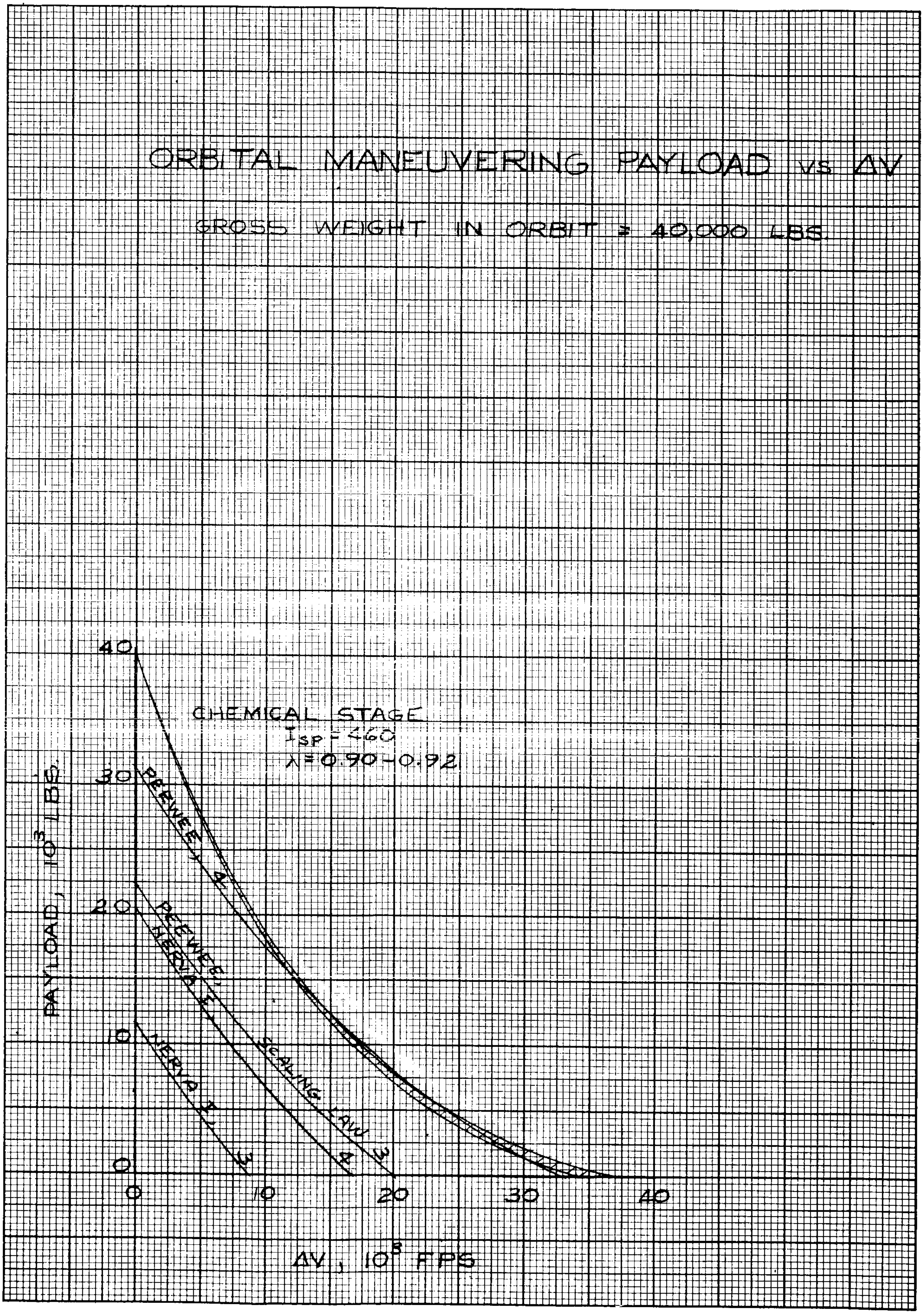

ORBITAL MANEUVERING PAYLOAD vs ΔV
GROSS WEIGHT IN ORBIT = 40,000 LBS.
CHEMICAL STAGE
I_{SP} = 460
λ = 0.90 - 0.92
PEEWEE, 4
PEEWEE, NERVA I
SCALING LAW
NERVA I
3
4
3
PAYLOAD, 10^3 LBS.
40
30
20
10
0
0
10
20
30
40
ΔV, 10^3 FPS

FIG. 6

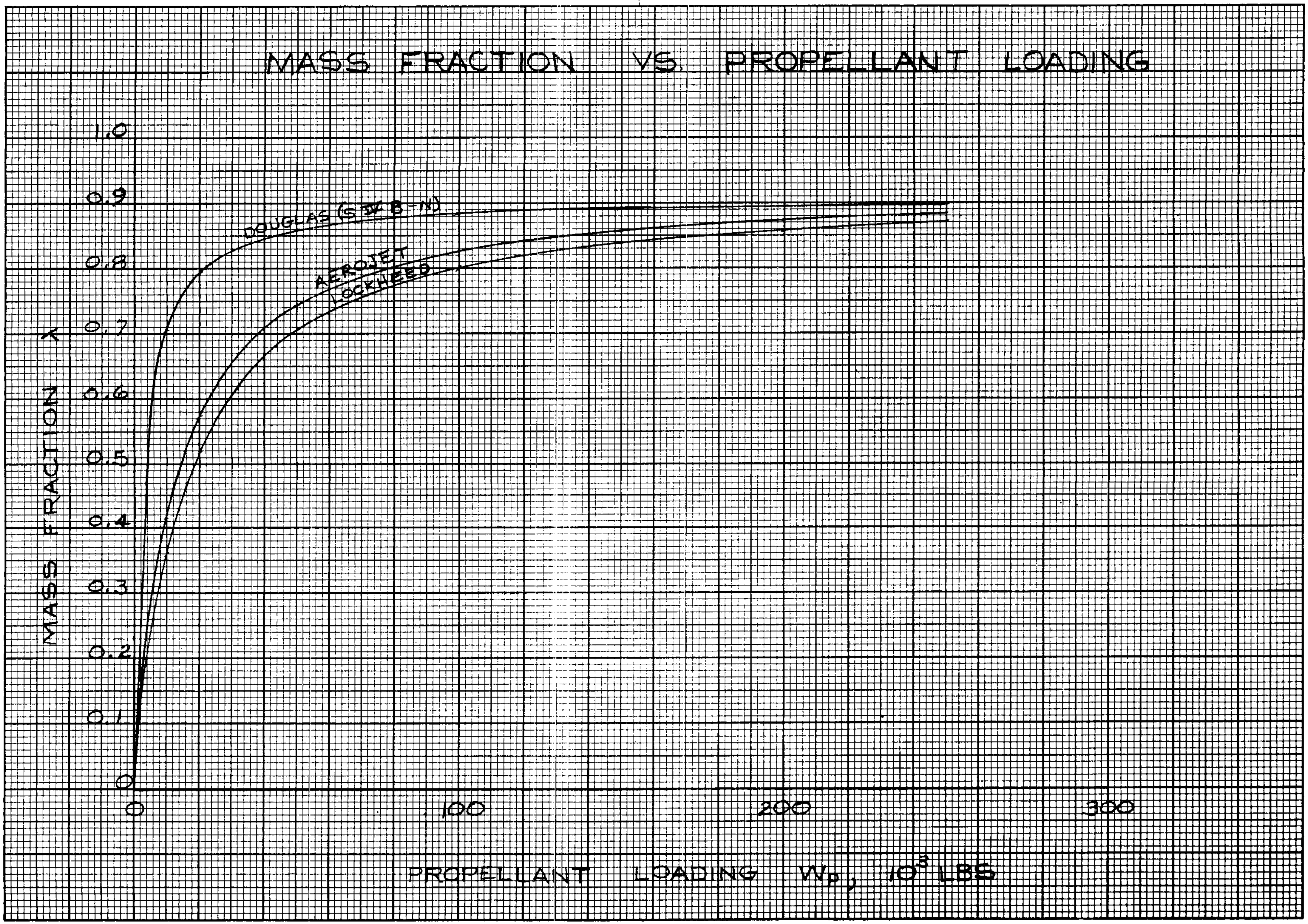

MASS FRACTION VS. PROPELLANT LOADING
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
MASS FRACTION λ
DOUGLAS (S IV B-N)
AEROJET
LOCKHEED
0
100
200
300
PROPELLANT LOADING W_P, 10^3 LBS

FIG. 7

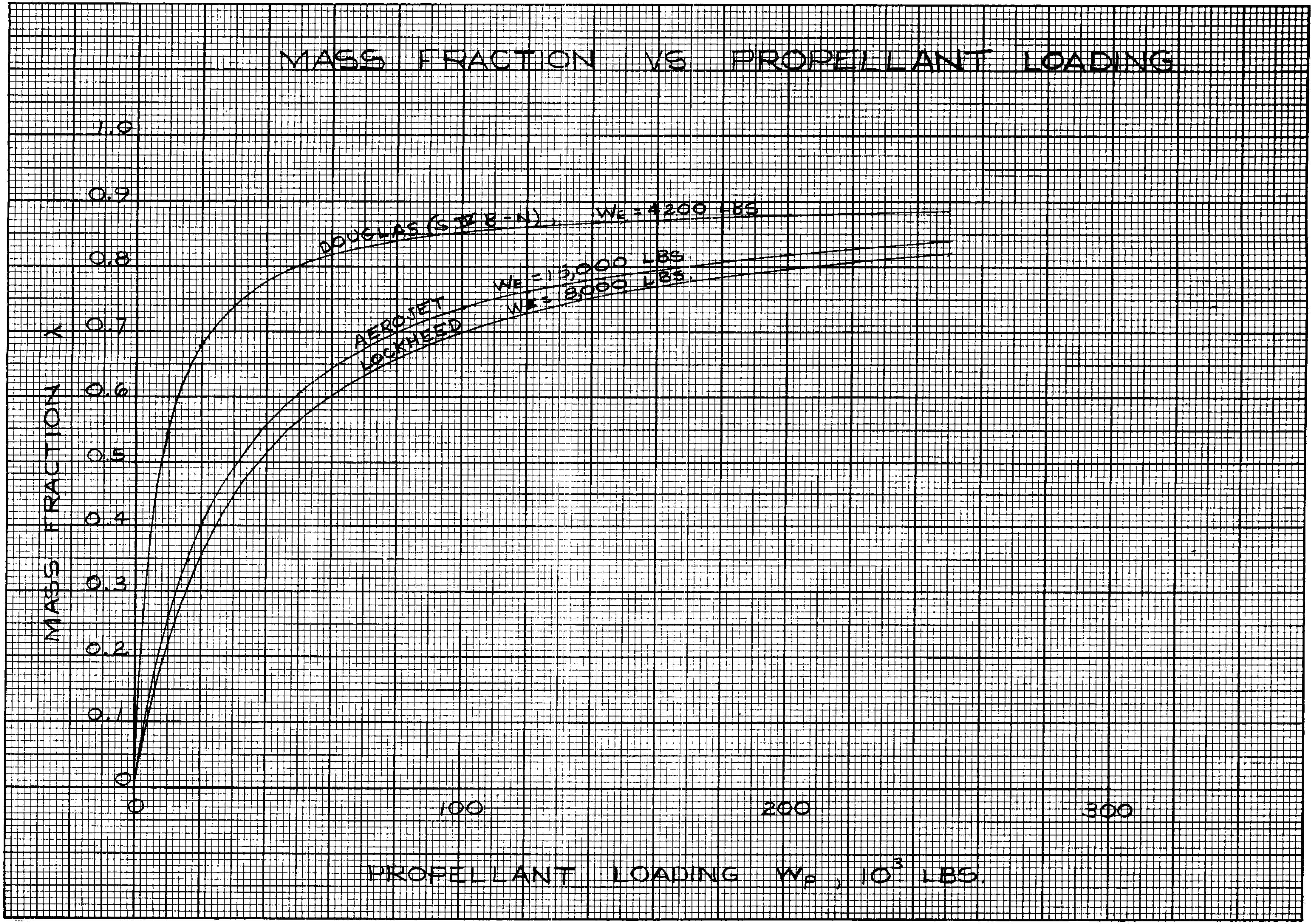

MASS FRACTION VS PROPELLANT LOADING
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
MASS FRACTION X
DOUGLAS (S IV B-N), WE = 4200 LBS
AEROJET WE = 15,000 LBS
LOCKHEED WE = 8,000 LBS
0
100
200
300
PROPELLANT LOADING WP, 10³ LBS.

FIG. 8

BELLCOMM, INC.

Subject: Comparison of Chemical and Nuclear Propulsion for Earth Orbital Maneuvering and Translunar Injection Stages - Case 720

From: H. S. London

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